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Laboratory Assessment of Commercially Available Ultrasonic Rangefinders

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14. ABSTRACT

The Auditory Protection and Performance Division at the United States Army Aeromedical Research Laboratory currently maps sound environments using a tape measure. The limitations of five different models of ultrasonic rangefinders were examined to gauge the viability of improving the process through the use of these rangefinders. The performance at different angles of incidence (0 to 40 degrees) at 0.5, 1.0, and 1.5 meters was investigated in locations with differing acoustical characteristics. Results from these tests suggested low accuracy performance with only 2.33 percent of the tests aligning with the actual distance. 86.67 percent of the tests exhibited significant differences in readings when examining the effect of angle of incidence. 100 percent of the tests exhibited significant differences with changes in location when examining the effect of room acoustics. These results suggest commercially available ultrasonic rangefinders are not an improvement, but there are a few limitations in the procedure that prevent this conclusion from being definitive.

15. SUBJECT TERMS

ultrasonic rangefinder, accuracy, process improvement

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Introduction

Prior to taking acoustic measurements in a particular environment, transducers and noise sources must first be spatially located. The United States Army Aeromedical Research Laboratory (USAARL) Auditory Protection and Performance Division currently maps environments for sound measurements using a tape measure. This mapping method can be time-consuming and unreliable as objects frequently move around in a particular environment.

One potential method of improving the process in both speed and accuracy is by using electronic rangefinders, particularly ultrasonic rangefinders. The choice of ultrasonic rangefinders was made because of their relative low cost and ease of use. These rangefinders work by producing ultrasonic pulses and timing the delay between pulse emission and reception of the echo in order to determine an object's distance. There are some uncertainties with using ultrasonic rangefinders that need to be tested, particularly the behavior of the rangefinders when the angle of incidence differs from zero.

From prior research, it is apparent that rangefinder measurements have some error involved depending on a variety of factors (Drumheller, 1985; Girard et al., 2011). One type of ultrasonic rangefinder, the PING™[*] ultrasonic sensor, demonstrated detection ability of a smooth wall approximately 1.4 meters (m) away at roughly a 40 degree angle (Karmali, Tomlinson, and Goyal, n.d.). Unfortunately, the study does not clearly report what distance is recorded when detecting the wall at that angle and only presents a figure that suggests that the ranging data are not accurate. Reverberation, or lack of it, is also a potential source of error that may differ in specialized (anechoic or reverberant) or smaller rooms (Girard et al., 2011).

The objective of this test was to determine the limitations of ultrasonic rangefinders with regard to angle of incidence and different room acoustic characteristics. The results of this testing will provide an indication of the operational conditions for these rangefinders and aid in judging the feasibility of using rangefinders to map different environments.

Methods

Several models of ultrasonic rangefinders were tested in a variety of different test scenarios. The rangefinders were set in different rooms at distances of 0.5, 1.0, and 1.5 meters away from a wall, with these distances being verified using a tape measure before each set of readings and if the system was visibly moved. These measurements were taken from where the zero point was located based on the technical specifications sheet for each sensor. The sensors were rotated to establish angles of incidence ranging from 0 to 40 degrees in 10 degree increments measured by a protractor. Data were acquired in a set of 10 readings at each distance and angle in four different testing locations via a button press. The testing locations included an anechoic chamber, common office space, a reverberant chamber, and a sound booth. Figure 1 below illustrates how the system was set up during data collection.

[*]See manufacturer's list.

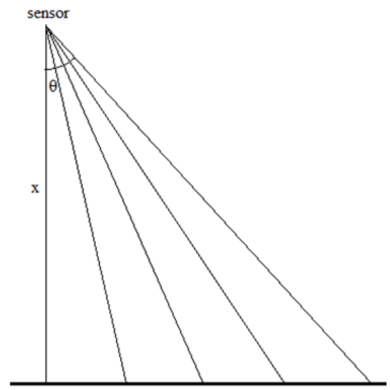

Figure 1. System arrangement schematic. Sensor was placed "x" (0.5, 1.0, 1.5) meters away from wall with an angle of "θ" (0, 10, 20, 30, 40) degrees.

In order to analyze measurement accuracy, *t*-tests were performed to determine if there were significant differences between the distances recorded by the rangefinders and the actual measured distance. An analysis of variance was performed to determine if there were significant differences among the data gathered at different angles of incidence. Additionally, an analysis of variance was performed again on the data to determine if there were significant differences among the data gathered in different sound environments.

Materials

The data acquisition system used in this study consisted of an ultrasonic rangefinder (MB1023 HRLV-MaxSonar®-EZ2™*, MB1043 HRLV-MaxSonar®-EZ4™, MB1220 XL-MaxSonar®-EZ2™, MB1240 XL-MaxSonar®-EZ4™, or MB1261 XL-MaxSonar®-EZL1™) and an Arduino Mega 2560* board to interface with MATLAB*. These sensors were chosen as a representative sample of ultrasonic rangefinders with different beam characteristics that could affect measurements. The Arduino board and ultrasonic rangefinder were connected to the computer via universal serial bus (USB) cable, which acted as both a power source and data transfer method. Based on the specification sheets of the rangefinders, each rangefinder differs in the maximum detection range with the MB1023 and MB1043 detecting up to 5 meters, the MB1220 and MB1240 detecting up to 7.65 meters, and the MB1261 detecting up to 10.68 meters. The MB1023 and MB1043 sensors have a resolution of 1 millimeter, while the MB1220, MB1240, and MB1261 sensors have a resolution of 1 centimeter. Additionally, each of these sensors has a different beam pattern. Each testing distance was measured using a tape measure, and the angles of incidence were measured using a protractor.

Results

Only 2.33 percent (7/300) of the tests produced results that were not significantly different from the actual distances. Figures 2 through 5 show the average distance calculated from 10 trials by each sensor, at each testing angle, and in each testing location at a physical distance of 0.5 meters away from a wall.

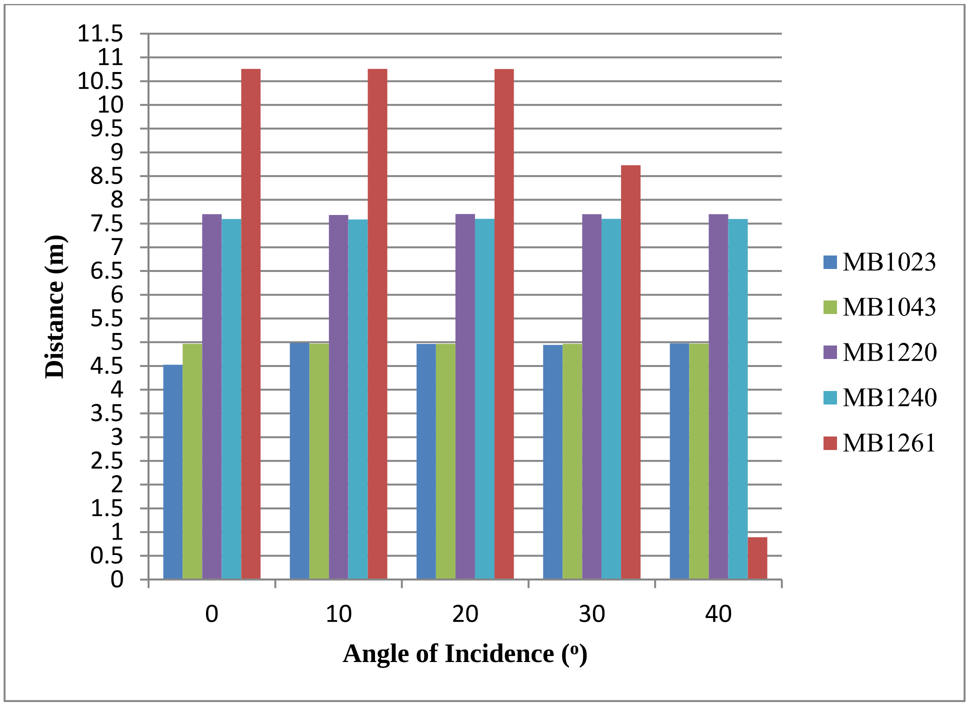

Figure 2. Sensor means in anechoic chamber at 0.5 m.

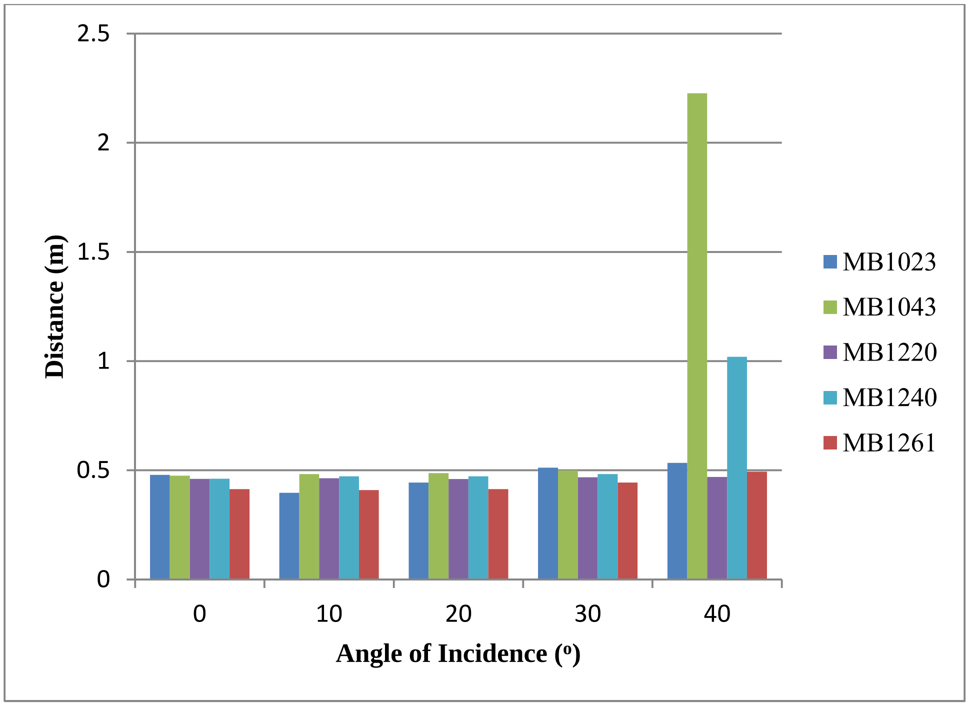

Figure 3. Sensor means in office space at 0.5 m.

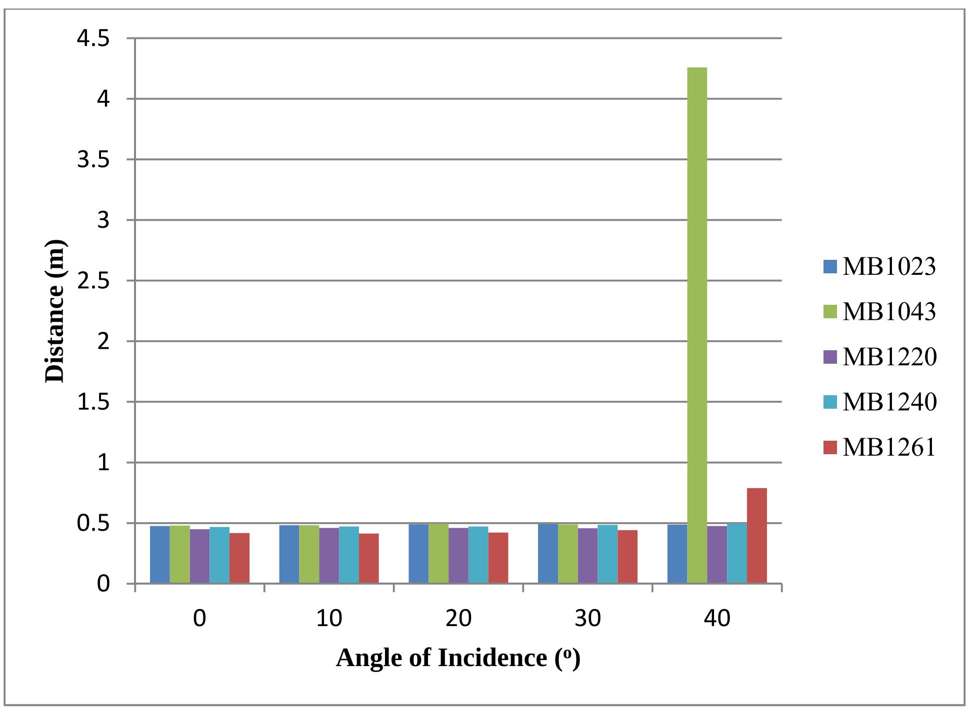

Figure 4. Sensor means in reverberant chamber at 0.5 m.

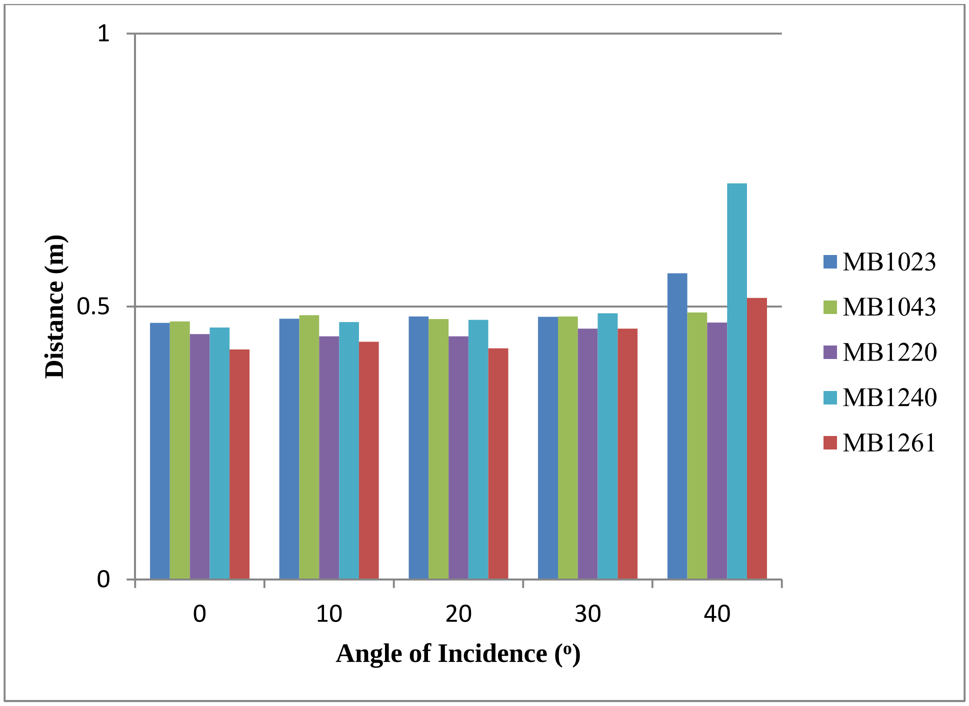

Figure 5. Sensor means in sound booth at 0.5 m.

Table 1 below summarizes the average distances and standard deviations from 10 readings at five different angles by the MB1023 sensor in office space. Tables of the means and standard deviations from all testing locations can be found in appendix A.

Table 1.
MB1023 means and standard deviations (office).

Angle of incidence	Mean (meters (m))			Standard deviation		
	0.5 m	1.0 m	1.5 m	0.5 m	1.0 m	1.5 m
0 °	0.41345	0.86504	1.42098	0.01036	0.10681	0.01271
10 °	0.40944	0.90718	1.42299	0.01036	0.00846	0.00636
20 °	0.41345	0.90116	1.42098	0.01403	0.01757	0.00847
30 °	0.44356	0.90116	1.42299	0.00635	0.00635	0.00636
40°	0.49373	0.90521	1.41695	0.06073	0.03048	0.41566

Table 2 summarizes the *p*-values generated from the data acquired by the MB1023 sensor placed at 0.5 meters from an office space wall. Based on these *p*-values, measurements from three different angles were not significantly different ($p > 0.05$) under the aforementioned conditions. Tables summarizing the *p*-values from all the tests can be found in appendix A.

Table 2.
MB1023 *t*-test *p*-values (office).

Comparing measured distance and actual distance.

Angle of incidence	*p*-value		
	0.5 m	1.0 m	1.5 m
0°	7.9770×10^{-07}	1.4476×10^{-06}	1.7816×10^{-08}
10°	0.1213	6.8887×10^{-12}	4.2816×10^{-14}
20°	0.2921	1.4862×10^{-15}	9.6890×10^{-15}
30°	4.8687×10^{-04}	1.3793×10^{-17}	3.7516×10^{-20}
40°	0.2970	2.8359×10^{-19}	1.5407×10^{-19}

The results from the ANOVA performed on data at different angles indicate that 86.67 percent (52/60) of the tests showed significant differences ($p < 0.05$). Table 3 summarizes the *p*-values obtained from data gathered in the reverberant chamber. The *p*-values presented here indicate that there are significant differences between data groups for each testing distance in the reverberant chamber. A full table listing the *p*-values from every testing condition can be found in appendix A.

Table 3.
ANOVA *p*-values (different angles, reverberant chamber).

Sensor model	*p*-value		
	0.5 m	1.0 m	1.5 m
MB1023	1.2021×10^{-11}	4.7141×10^{-69}	2.4313×10^{-05}
MB1043	1.8830×10^{-22}	1.6774×10^{-19}	2.1691×10^{-14}
MB1220	2.8877×10^{-13}	4.6723×10^{-63}	3.8896×10^{-59}
MB1240	9.6990×10^{-21}	4.0595×10^{-61}	1.7949×10^{-12}
MB1261	3.0671×10^{-31}	0.0249	8.4844×10^{-09}

The results from the ANOVA performed on data acquired in different locations indicate that there were significant differences for all sensors at all distances. The *p*-values generated from the ANOVA test are listed in table 4 and are all less than 0.05.

Table 4.
ANOVA *p*-values (different locations).

Sensor model	*p*-values		
	0.5 m	1.0 m	1.5 m
MB1023	1.8840×10^{-39}	5.8767×10^{-95}	2.9651×10^{-45}
MB1043	2.7059×10^{-17}	8.0615×10^{-87}	3.2895×10^{-98}
MB1220	7.4747×10^{-96}	1.5886×10^{-69}	3.0461×10^{-103}
MB1240	5.4754×10^{-51}	6.9079×10^{-103}	3.6820×10^{-77}
MB1261	2.3828×10^{-25}	7.8747×10^{-87}	2.9245×10^{-12}

Discussion

The means of the data are summarized in tables A-1, A-2, A-3, and A-4 (appendix A). Based on these means, the ultrasonic rangefinders generally underestimated the actual distance. The p-values generated by the *t*-tests comparing the measured distance to the actual distance suggest that the data are significantly different. Only 2.33 percent (7/300) of the tests yielded a *p*-value greater than 0.05. In the anechoic chamber, the rangefinders performed exceptionally poorly, potentially from how the room was designed to prevent sound reflections (a combination of the wedges absorbing the waveforms and not having a flat wall). When testing in the anechoic chamber, the sensors appeared to record the maximum distance possible but underestimated that distance. The potential underestimation of maximum distance may possibly indicate an inherent underestimation in the sensors, but requires further testing to validate. The underestimation of the distances may also be a result of the data acquisition system. The system used to conduct the test may have been calculating the distance from the voltage differently either because of voltage influence by the power source or the conversion from voltage to distance. One method of mitigating that potential limitation is by connecting a dedicated power source rather than using a USB cable for both power and data transfer. Another source of error could stem from the "true" distance being measured using a tape measure that can bend at greater distances. Future testing should mitigate this error by using a measurement device whose accuracy cannot be easily altered.

The sensors were generally sensitive enough to record different distances due to changes in the angle of incidence. The ANOVA comparing data gathered at different angles of incidence suggests that there are some significant differences in data from different angles of incidence, with 52 out of 60 tests reporting a *p*-value less than 0.05. Data acquired at a 40^{o} angle of incidence were generally different from data acquired at any other angle of incidence. Differences in data acquired at a 0^{o}, 10^{o}, 20^{o}, or 30^{o} angle of incidence were not as prominent when comparing amongst themselves. The recorded distances may differ at different angles of incidence because the actual change in distance may not be greater than the resolution of the sensor.

Locations with different acoustical characteristics appear to have an impact on the reading recorded by the ultrasonic rangefinders. The ANOVA performed on the data acquired from different locations indicate that there are significant differences in all scenarios, with all tests reporting a *p*-value less than 0.05. Differences in data were visually apparent when comparing data acquired in the anechoic chamber and data acquired in any other testing location. Differences in data were not as prominent among data gathered in an office, the reverberant chamber, or a sound booth.

Conclusions

The results of this testing suggest that ultrasonic rangefinders are not an improvement over the conventional tape measure in mapping an environment accurately for sound measurements. While these results generally suggest that the rangefinders are statistically inaccurate, data gathered in the anechoic chamber suggest that more data should be collected at the upper ranges for each sensor to determine if there is inherent underestimation that could affect the results presented here. With regard to the effect of different angles of incidence, the results from the testing suggest that the sensors' distance readings changed as the angle of incidence changed. On inspection of the data, distances recorded at a 40^{o} angle of incidence were generally larger than distances recorded at a 0^{o} angle of incidence regardless of location. The ultrasonic rangefinders also performed differently in rooms with differing acoustical characteristics. There is a large discrepancy in the distances acquired by the sensors in the anechoic chamber versus any other location. The sensors' potential underestimation of distance based on data gathered in the anechoic chamber indicate that the data gathered may not be sufficient to definitively determine that the rangefinders are not an improvement in the other locations. Further testing should be performed to definitively determine the viability of using ultrasonic rangefinders to map environments for sound measurement.

References

Drumheller, M. 1987. Mobile robot localization using sonar. IEEE Transaction on Pattern Analysis and Machine Intelligence. 9(2): 325-32.

Girard, G., Côte, S., Zlatanova, S., Barette, Y., St-Pierre, J., and van Oosterom, P. 2011. Indoor pedestrian navigation using foot-mounted IMU and portable ultrasound range sensors. Sensors. 11(8): 7606-24.

Karmali, F., Tomlinson, A., Goyal, H. n.d. Characterization of a parallax ping)))™ ultrasonic range finder. http://www.eng.auburn.edu/~troppel/courses/5530 2011C Robots Fall 11/projects/project submissions/written13.pdf

Appendix A.

Data tables.

Table A-1.
Means and standard deviations (anechoic chamber).

Data calculated from 10 readings.

Sensor model	Angle of incidence	Mean			Standard deviation		
		0.5 m	1.0 m	1.5 m	0.5 m	1.0 m	1.5 m
MB1023	0 ^{o}	4.5274	4.53197	4.9795	1.44268	1.41767	0.00453
	10 ^{o}	4.98299	4.984	4.986	0.00688	0.00337	0.0053
	20 ^{o}	4.96341	4.98149	4.60666	0.02778	0.00397	0.64769
	30 ^{o}	4.9429	4.987	2.42752	0.02312	0.00158	0.06003
	40^{o}	4.97798	4.9865	4.92179	0.01121	0.00316	0.17439
MB1043	0 ^{o}	4.96591	4.97444	4.97493	0.00711	0.00263	0.00356
	10 ^{o}	4.9719	2.04567	4.97141	0.00158	0.04826	0.00318
	20 ^{o}	4.9674	4.9659	4.97241	0.00577	0.0058	0.00238
	30 ^{o}	4.9679	4.97192	4.97343	0.00798	0.00372	0.0032
	40^{o}	4.97091	4.97244	4.9664	0.00413	0.00531	0.00211
MB1220	0 ^{o}	7.6981	7.696	7.697	0.00567	0.00316	9.4×10^{-16}
	10 ^{o}	7.68197	7.696	7.688	0.00976	0.00316	0.00316
	20 ^{o}	7.7	7.697	7.698	0.00483	9.4×10^{-16}	0.00568
	30 ^{o}	7.697	7.697	7.696	9.4×10^{-16}	9.4×10^{-16}	0.00316
	40^{o}	7.698	7.698	7.697	0.00316	0.00316	0.00471
MB1240	0 ^{o}	7.5956	7.5876	3.58659	0.00316	0.00316	0.61287
	10 ^{o}	7.5866	7.5966	3.35779	0	0	0.09971
	20 ^{o}	7.60031	7.5946	3.44308	0.00422	0.00225	0.10239
	30 ^{o}	7.59852	7.5966	3.40916	0	0.00572	0.08815
	40^{o}	7.59761	7.59661	3.38086	0.00474	0.00319	0.00998
MB1261	0 ^{o}	10.7577	10.7577	10.7577	0	0	0
	10 ^{o}	10.7597	10.7577	10.7577	0.01139	0.00945	0
	20 ^{o}	10.7557	10.7577	10.7557	0.00632	0	0.00632
	30 ^{o}	8.72821	10.7597	1.16209	4.12998	0.00636	0.00636
	40^{o}	0.89113	10.7457	1.16209	0.04036	0.01033	0.00636

Table A-2.
Means and standard deviations (office).

Data calculated from 10 readings.

Sensor model	Angle of incidence	Mean			Standard deviation		
		0.5 m	1.0 m	1.5 m	0.5 m	1.0 m	1.5 m
MB1023	0^{o}	0.47868	0.98395	1.47219	0.00485	0.0037	0.00423
	10^{o}	0.39689	0.98245	1.4807	0.1993	0.00212	0.00158
	20^{o}	0.44402	0.98445	1.4847	0.2404	0.00212	0.00369
	30^{o}	0.51179	0.97793	1.4812	0.03725	0.00285	0.00211
	40^{o}	0.53387	0.98847	1.49121	0.33087	0.00334	0.00462
MB1043	0^{o}	0.47567	0.98245	1.4757	0.00461	0.00317	0.00284
	10^{o}	0.48269	0.98044	1.4762	0.00317	0.00423	0.00394
	20^{o}	0.48721	0.98747	1.4782	0.00687	0.00212	0.00258
	30^{o}	0.49972	0.98947	1.4872	0.00677	0.00211	0.00258
	40^{o}	2.22681	2.8544	2.1365	1.3679	0.01161	0.00316
MB1220	0^{o}	0.46062	0.95434	1.4561	0.0057	0.00317	0.00316
	10^{o}	0.46363	0.95334	1.4561	0.00423	1.2×10^{-16}	0.00316
	20^{o}	0.45961	0.95334	1.4651	0.00423	1.2×10^{-16}	2.3×10^{-16}
	30^{o}	0.46764	0.96338	1.4852	0.00518	1.2×10^{-16}	0.00471
	40^{o}	0.46964	0.96739	1.49924	0.00423	0.00969	0.00522
MB1240	0^{o}	0.46162	0.9704	1.4832	5.9×10^{-17}	0.00484	0.00422
	10^{o}	0.47265	0.96739	1.4852	0.00317	0.00518	2.3×10^{-16}
	20^{o}	0.47265	0.97542	1.4932	0.00317	0.00423	0.00422
	30^{o}	0.48269	0.97542	1.49521	0.00317	0.00423	0.00474
	40^{o}	1.0196	0.99849	2.15558	0.24386	0.00528	0.00426
MB1261	0^{o}	0.41345	0.86504	1.42098	0.01036	0.10681	0.01271
	10^{o}	0.40944	0.90718	1.42299	0.01036	0.00846	0.00636
	20^{o}	0.41345	0.90116	1.42098	0.01403	0.01757	0.00847
	30^{o}	0.44356	0.90116	1.42299	0.00635	0.00635	0.00636
	40^{o}	0.49373	0.90521	1.41695	0.06073	0.03048	0.41566

Table A-3.
Means and standard deviations (reverberant chamber).

Data calculated from 10 readings.

Sensor model	Angle of incidence	Mean			Standard deviation		
		0.5 m	1.0 m	1.5 m	0.5 m	1.0 m	1.5 m
MB1023	0^{o}	0.47617	0.98897	1.4792	0.00285	0.00158	0.00211
	10^{o}	0.48219	0.98797	1.4812	0.00285	0.00285	0.00316
	20^{o}	0.48972	0.98947	1.4867	0.00259	0.00211	0.00337
	30^{o}	0.49122	0.99398	1.49622	0.0037	0.00159	0.00215
	40^{o}	0.48771	1.27899	2.11893	0.0057	0.00646	0.67472
MB1043	0^{o}	0.47918	0.98947	1.45913	0.00265	0.00317	0.01416
	10^{o}	0.48219	0.98947	1.4817	0.00159	0.00211	0.00242
	20^{o}	0.49574	0.99248	1.4922	0.00617	0.00211	0.00258
	30^{o}	0.48871	0.99699	2.23583	0.00259	0.00338	0.93638
	40^{o}	4.25892	3.97342	3.84846	1.14884	1.07678	0.65367
MB1220	0^{o}	0.44957	0.96639	1.4641	0.00423	0.00484	0.00316
	10^{o}	0.45961	0.96438	1.4651	0.00423	0.00317	2.3×10^{-16}
	20^{o}	0.45961	0.96438	1.4651	0.00423	0.00317	2.3×10^{-16}
	30^{o}	0.4566	0.96438	1.4852	0.00529	0.00317	2.3×10^{-16}
	40^{o}	0.47567	1.23231	1.66883	0.00702	0.00635	0.00827
MB1240	0^{o}	0.46764	0.97843	1.4842	0.00518	0.00529	0.00316
	10^{o}	0.47165	0.98044	1.4852	0	0.00485	2.3×10^{-16}
	20^{o}	0.47165	0.97743	1.50022	0	0.00518	0.01587
	30^{o}	0.4847	1.00049	1.5113	0.00484	0.00484	0.00516
	40^{o}	0.49574	1.29051	2.89515	0.00518	0.00701	0.79173
MB1261	0^{o}	0.41747	0.92123	1.41696	0.00846	0.00635	0.01038
	10^{o}	0.41345	0.91521	1.425	0.01036	0.01036	2.3×10^{-16}
	20^{o}	0.42148	0.92525	1.425	0.00946	0.00635	2.3×10^{-16}
	30^{o}	0.44155	0.92324	1.44308	0	1.2×10^{-16}	0.01139
	40^{o}	0.78877	0.92123	1.57754	0.06694	0.00635	0.11282

Table A-4.
Means and standard deviations (sound booth).

Data calculated from 10 readings.

Sensor model	Angle of incidence	Mean			Standard deviation		
		0.5 m	1.0 m	1.5 m	0.5 m	1.0 m	1.5 m
MB1023	0°	0.47012	0.98496	1.47219	0.00246	0.00242	0.00352
	10°	0.47767	0.98997	1.46918	0.00317	0.00338	0.00215
	20°	0.48169	0.98997	1.4752	0.00335	0.00242	0.00236
	30°	0.48119	0.98897	1.4802	0.00285	0.00158	0.00236
	40°	0.56097	1.15755	2.17758	0.00317	0.25782	0.00245
MB1043	0°	0.47266	0.98395	1.4767	0.00317	0.00285	0.00337
	10°	0.4842	0.98295	1.4812	0.00265	0.00159	0.00316
	20°	0.47717	0.98496	1.4817	0.0037	0.00339	0.00242
	30°	0.48169	1.37731	2.2002	5.9×10^{-17}	0.48905	0.00264
	40°	0.48922	1.59709	2.1932	0.00426	0.00946	0.00284
MB1220	0°	0.44957	0.95234	1.4551	0.00423	0.00317	0
	10°	0.44556	0.95434	1.4531	0.00518	0.00317	0.00422
	20°	0.44556	0.95334	1.4551	0.00518	1.2×10^{-16}	0
	30°	0.45961	0.95535	1.4641	0.00423	0.00423	0.00316
	40°	0.47065	0.97943	1.80933	0.00317	0.00846	0.00827
MB1240	0°	0.46162	0.9694	1.46511	5.9×10^{-17}	0.00518	0.01158
	10°	0.47165	0.97241	1.47318	0	0.00317	0.00426
	20°	0.47567	0.93776	1.4842	0.0127	0.07148	0.00316
	30°	0.48771	0.98445	1.51732	0.01583	0.00317	0.00426
	40°	0.72554	1.58759	2.19469	0.00485	0.00791	0.00952
MB1261	0°	0.42148	0.88711	1.4049	5.9×10^{-17}	0.00846	2.3×10^{-16}
	10°	0.43553	0.88711	1.4029	0.00969	0.00846	0.00632
	20°	0.42349	0.89715	1.4049	0.00635	0.00969	2.3×10^{-16}
	30°	0.45961	0.90518	1.42902	0.02403	0.00635	0.00847
	40°	0.51581	0.92324	1.71402	0.01355	1.2×10^{-16}	0.07401

Table A-5.

T-test *p*-values (anechoic chamber).

Data compares actual and measured distances.

Distance (m)	Angle of incidence	*p*-value				
		MB1023	MB1043	MB1220	MB1240	MB1261
0.5	0^{o}	9.9360 x 10^{-06}	1.0500 x 10^{-26}	1.8602 x 10^{-29}	1.1125 x 10^{-31}	0
	10^{o}	7.6441 x 10^{-27}	1.4038 x 10^{-32}	2.5563 x 10^{-27}	0	4.1356 x 10^{-28}
	20^{o}	2.3967 x 10^{-21}	1.7174 x 10^{-27}	4.5983 x 10^{-30}	5.2814 x 10^{-33}	2.1309 x 10^{-30}
	30^{o}	5.2345 x 10^{-22}	3.4469 x 10^{-26}	0	2.5236 x 10^{-29}	1.5084 x 10^{-04}
	40^{o}	8.4338 x 10^{-25}	1.0808 x 10^{-28}	1.1861 x 10^{-31}	1.4760 x 10^{-31}	1.4823 x 10^{-08}
1.0	0^{o}	2.4840 x 10^{-05}	3.9394 x 10^{-30}	1.8740 x 10^{-31}	2.1704 x 10^{-31}	0
	10^{o}	3.7185 x 10^{-29}	1.6894 x 10^{-13}	1.9133 x 10^{-31}	3.8262 x 10^{-144}	1.2226 x 10^{-28}
	20^{o}	1.8012 x 10^{-28}	5.6458 x 10^{-27}	0	3.1265 x 10^{-30}	6.0118 x 10^{-143}
	30^{o}	5.5387 x 10^{-32}	1.2754 x 10^{-28}	0	0	3.9078 x 10^{-30}
	40^{o}	4.0728 x 10^{-29}	4.4945 x 10^{-27}	2.8441 x 10^{-31}	1.2488 x 10^{-29}	3.6048 x 10^{-28}
1.5	0^{o}	1.7299 x 10^{-27}	1.9830 x 10^{-28}	6.5729 x 10^{-144}	1.9059 x 10^{-06}	0
	10^{o}	7.3224 x 10^{-27}	7.7828 x 10^{-29}	3.9415 x 10^{-31}	6.4930 x 10^{-13}	0
	20^{o}	1.3344 x 10^{-07}	6.8854 x 10^{-30}	8.3670 x 10^{-29}	7.7651 x 10^{-13}	5.7285 x 10^{-30}
	30^{o}	4.0114 x 10^{-11}	1.4407 x 10^{-28}	5.3101 x 10^{-31}	4.8031 x 10^{-13}	4.5025 x 10^{-19}
	40^{o}	1.3321 x 10^{-12}	6.5054 x 10^{-30}	2.7285 x 10^{-29}	6.5218 x 10^{-21}	2.1977 x 10^{-20}

Table A-6.
T-test *p*-values (office).

Data compares actual and measured distances.

Distance (m)	Angle of incidence	*p*-value				
		MB1023	MB1043	MB1220	MB1240	MB1261
0.5	0^o	7.9970×10^{-07}	1.4056×10^{-07}	8.3294×10^{-09}	0	1.0587×10^{-09}
	10^o	1.2128×10^{-01}	4.0207×10^{-09}	2.0082×10^{-10}	1.4232×10^{-10}	3.2886×10^{-10}
	20^o	2.9208×10^{-01}	1.2626×10^{-08}	1.8384×10^{-12}	8.9845×10^{-13}	8.7092×10^{-10}
	30^o	4.8687×10^{-04}	6.4672×10^{-11}	2.3864×10^{-13}	1.1407×10^{-14}	2.3810×10^{-13}
	40^o	2.9696×10^{-01}	5.3515×10^{-03}	3.4946×10^{-16}	9.7829×10^{-04}	1.9612×10^{-05}
1.0	0^o	1.4476×10^{-06}	1.5174×10^{-07}	1.1062×10^{-11}	3.1507×10^{-08}	3.5816×10^{-03}
	10^o	6.8887×10^{-12}	1.8801×10^{-09}	0	5.4012×10^{-10}	2.2091×10^{-11}
	20^o	1.4862×10^{-15}	2.1306×10^{-15}	0	2.7764×10^{-13}	3.5802×10^{-10}
	30^o	1.3793×10^{-17}	1.7316×10^{-18}	0	4.2669×10^{-16}	6.9011×10^{-16}
	40^o	2.8359×10^{-19}	1.1778×10^{-20}	2.2806×10^{-15}	2.3229×10^{-17}	1.4539×10^{-11}
1.5	0^o	1.7816×10^{-08}	1.9985×10^{-09}	1.5553×10^{-11}	2.6853×10^{-06}	1.4873×10^{-08}
	10^o	4.2816×10^{-14}	5.9127×10^{-11}	2.7856×10^{-13}	0	3.4819×10^{-12}
	20^o	9.6890×10^{-15}	2.3180×10^{-16}	0	6.6970×10^{-14}	2.6913×10^{-13}
	30^o	3.7516×10^{-20}	2.8997×10^{-19}	6.0632×10^{-17}	9.2472×10^{-17}	1.1553×10^{-16}
	40^o	1.5407×10^{-19}	2.3927×10^{-17}	5.4055×10^{-19}	1.4160×10^{-16}	2.6997×10^{-03}

Table A-7.
T-test *p*-values (reverberant chamber).

Data compares actual and measured distances.

Distance (m)	Angle of incidence	*p*-value				
		MB1023	MB1043	MB1220	MB1240	MB1261
0.5	0°	2.5215×10^{-09}	5.2091×10^{-09}	5.5745×10^{-11}	2.3784×10^{-08}	2.6994×10^{-10}
	10°	1.2622×10^{-09}	6.7910×10^{-12}	8.8143×10^{-11}	0	4.8258×10^{-10}
	20°	3.6191×10^{-12}	3.6134×10^{-08}	1.8384×10^{-12}	0	4.9135×10^{-11}
	30°	1.0959×10^{-13}	3.3643×10^{-15}	1.1946×10^{-13}	6.2633×10^{-13}	0
	40°	1.3149×10^{-14}	3.7788×10^{-06}	4.5115×10^{-14}	8.9260×10^{-15}	1.0280×10^{-04}
1.0	0°	6.3423×10^{-08}	3.6582×10^{-05}	9.1614×10^{-09}	1.4943×10^{-06}	3.1863×10^{-11}
	10°	6.0168×10^{-10}	7.3882×10^{-11}	3.7749×10^{-12}	6.2665×10^{-09}	2.7478×10^{-10}
	20°	2.6822×10^{-15}	3.9423×10^{-15}	6.9855×10^{-15}	2.1197×10^{-12}	1.6844×10^{-13}
	30°	1.7065×10^{-19}	1.8421×10^{-16}	1.8404×10^{-17}	5.6598×10^{-15}	0
	40°	1.1338×10^{-06}	2.5891×10^{-05}	6.3798×10^{-11}	4.5413×10^{-04}	1.5821×10^{-17}
1.5	0°	7.0142×10^{-10}	1.4194×10^{-05}	1.0899×10^{-10}	4.4354×10^{-07}	1.5705×10^{-09}
	10°	2.4144×10^{-11}	2.4219×10^{-12}	0	0	0
	20°	5.1386×10^{-15}	7.4464×10^{-16}	0	1.7740×10^{-08}	0
	30°	7.8696×10^{-20}	1.2116×10^{-01}	0	3.8124×10^{-16}	4.0321×10^{-14}
	40°	4.6228×10^{-01}	7.3935×10^{-06}	2.2601×10^{-15}	4.5223×10^{-03}	2.2286×10^{-06}

Table A-8.
T-test *p*-values (sound booth).

Data compares actual and measured distances.

Distance (m)	Angle of incidence	*p*-value				
		MB1023	MB1043	MB1220	MB1240	MB1261
0.5	0^{o}	7.0281×10^{-11}	1.6415×10^{-09}	5.5745×10^{-11}	0	6.1816×10^{-143}
	10^{o}	6.4953×10^{-10}	1.4966×10^{-09}	4.7374×10^{-11}	0	3.1225×10^{-09}
	20^{o}	6.8947×10^{-12}	7.5700×10^{-12}	2.1521×10^{-12}	3.1791×10^{-07}	1.6255×10^{-12}
	30^{o}	3.7605×10^{-15}	9.8089×10^{-144}	2.0294×10^{-14}	3.2422×10^{-08}	1.0647×10^{-07}
	40^{o}	1.5398×10^{-14}	1.0413×10^{-15}	2.7616×10^{-17}	2.8369×10^{-12}	1.7222×10^{-10}
1.0	0^{o}	7.5593×10^{-08}	1.5322×10^{-07}	7.2611×10^{-12}	4.0882×10^{-08}	1.5007×10^{-11}
	10^{o}	5.9378×10^{-09}	6.0675×10^{-13}	6.9389×10^{-13}	1.9414×10^{-11}	4.6240×10^{-12}
	20^{o}	9.7024×10^{-15}	1.0834×10^{-13}	0	4.0043×10^{-04}	1.3991×10^{-12}
	30^{o}	1.2649×10^{-19}	1.7862×10^{-01}	1.6175×10^{-16}	5.1023×10^{-17}	7.9802×10^{-16}
	40^{o}	1.0935×10^{-01}	5.8208×10^{-15}	9.3512×10^{-16}	1.5512×10^{-15}	7.9933×10^{-144}
1.5	0^{o}	3.4706×10^{-09}	1.4123×10^{-08}	0	1.1135×10^{-05}	0
	10^{o}	6.7850×10^{-14}	2.4144×10^{-11}	2.4435×10^{-12}	6.4798×10^{-11}	6.1633×10^{-13}
	20^{o}	8.0977×10^{-17}	1.6786×10^{-16}	0	2.3243×10^{-15}	0
	30^{o}	9.8753×10^{-20}	8.6251×10^{-22}	7.9096×10^{-19}	8.6598×10^{-17}	1.8379×10^{-15}
	40^{o}	3.8584×10^{-19}	7.8238×10^{-19}	9.7307×10^{-13}	3.9483×10^{-14}	2.7925×10^{-06}

Table A-9.
ANOVA *p*-values (different angles).

Location	Distance (m)	*p*-value				
		MB1023	MB1043	MB1220	MB1240	MB1261
Anechoic Chamber	0.5	0.4535	0.1297	1.5651×10^{-08}	6.2360×10^{-11}	1.4900×10^{-16}
	1.0	0.4072	4.3769×10^{-78}	0.3382	6.4654×10^{-08}	2.3429×10^{-04}
	1.5	2.0023×10^{-24}	8.5502×10^{-07}	2.1328×10^{-06}	0.4129	1.6394×10^{-134}
Office	0.5	0.5879	2.7653×10^{-08}	3.8766×10^{-05}	4.6733×10^{-16}	5.1845×10^{-08}
	1.0	1.2044×10^{-08}	3.7488×10^{-95}	9.0219×10^{-10}	3.0414×10^{-18}	0.3251
	1.5	3.0094×10^{-14}	2.1543×10^{-87}	1.2418×10^{-30}	6.1031×10^{-83}	1.0000
Reverberant Chamber	0.5	1.2021×10^{-11}	1.8830×10^{-22}	2.8877×10^{-13}	9.6990×10^{-21}	3.0671×10^{-31}
	1.0	4.7141×10^{-69}	1.6774×10^{-19}	4.6723×10^{-63}	4.0595×10^{-61}	0.0249
	1.5	2.4313×10^{-05}	2.1691×10^{-14}	3.8896×10^{-59}	1.7949×10^{-12}	8.4844×10^{-09}
Sound Booth	0.5	1.5212×10^{-47}	1.4568×10^{-14}	2.4442×10^{-17}	5.4533×10^{-47}	1.8472×10^{-20}
	1.0	0.0049	1.3162×10^{-08}	1.6800×10^{-17}	1.8590×10^{-40}	1.9506×10^{-14}
	1.5	7.7593×10^{-92}	4.3606×10^{-94}	3.2443×10^{-68}	8.2303×10^{-72}	2.5376×10^{-26}

Appendix B.

Manufacturer's list.

Arduino LLC
https://www.arduino.cc/

The MathWorks®, Inc.
3 Apple Hill Drive
Natick, MA 01760-2098
http://www.mathworks.com/

MaxBotix® Inc.
13860 Shawkia Drive
Brainerd, MN 56401
http://www.maxbotix.com/

Parallax Inc.
599 Menlo Drive, Suite 100
Rocklin, CA 95765
https://www.parallax.com

Department of the Army
U.S. Army Aeromedical Research Laboratory
Fort Rucker, Alabama, 36362-0577
www.usaarl.army.mil

U.S. Army Medical Research and Materiel Command